

KFKI - 1999 - 06/A

# SIGNAL OF PARTIAL $U_A(1)$ SYMMETRY RESTORATION FROM TWO-PION BOSE-EINSTEIN CORRELATIONS

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The intercept parameter of the two-pion Bose-Einstein correlation functions at low  $p_t$  is shown to play the role of an *experimentally accessible measure* of the (partial) restoration of  $U_A(1)$  symmetry in ultra-relativistic nuclear collisions.

## 1 $U_A(1)$ symmetry restoration and the core-halo model

In this conference contribution, we follow the lines of ref. <sup>1</sup> to show that a link exists between the symmetry properties of hot and dense hadronic matter and the strength of the two-pion Bose-Einstein correlation functions.

In the chiral limit ( $m_u = m_d = m_s = 0$ ), QCD possesses a  $U(3)$  chiral symmetry. When broken spontaneously,  $U(3)$  implies the existence of nine massless Goldstone bosons. In nature, however, there are only eight light pseudoscalar mesons, a discrepancy which is resolved by the Adler-Bell-Jackiw  $U_A(1)$  anomaly; the ninth would-be Goldstone boson gets a mass as a consequence of the nonzero density of topological charges in the QCD vacuum <sup>2,3</sup>. In recent papers <sup>4,5</sup>, it was argued that the partial restoration of  $U_A(1)$  symmetry of QCD and related decrease of the  $\eta'$  mass <sup>6,7,8,9</sup> in regions of sufficiently hot and dense matter should manifest itself in a factor of 3 to 50 increase <sup>4</sup> in the production of  $\eta'$  mesons, relative to nuclear interactions which do not produce the phase transition.

It was also observed, however, that the  $\eta'$  decays are characterized by a small signal-to-background ratio in the direct two-photon decay mode. We have shown in ref. <sup>1</sup>, that the momentum dependence of  $\lambda_*$ , that characterizes the strength of Bose-Einstein correlations of pions, provides an experimentally well observable signal for partial  $U_A(1)$  restoration.

As was shown in several papers<sup>10,11</sup>, at incident beam energies of 200 AGeV at the CERN SPS, the space-time structure of pion emission in high energy nucleus-nucleus collisions can be separated into two regions: the *core* and the *halo*. The pions which are emitted from the core or central region are either produced from a direct production mechanism such as the hadronization of wounded string-like nucleons in the collision region, rescattering as they flow outward with a rescattering time on the order of 1 fm/c, or they are produced from the decays of short-lived hadronic resonances such as the  $\rho$ ,  $N^*$ ,  $\Delta$  and  $K^*$ , whose decay time is also on the order of 1-2 fm/c. This core region is resolvable by Bose-Einstein correlation (BEC) measurements. The halo region, however, consists of the decay products of long-lived hadronic resonances such as the  $\omega$ ,  $\eta$ ,  $\eta'$  and  $K_S^0$  whose lifetime is greater than 20 fm/c. This halo region is not resolvable by BEC measurements but it contributes to the reduction of the effective intercept parameter,  $\lambda_*$ .

The two-particle Bose-Einstein correlation function is defined as

$$C(\Delta k, K) = \frac{N_2(\mathbf{p}_1, \mathbf{p}_2)}{N_1(\mathbf{p}_1)N_1(\mathbf{p}_2)}, \quad (1)$$

where the inclusive 1 and 2-particle invariant momentum distributions are

$$N_1(\mathbf{p}_1) = \frac{1}{\sigma_{in}} E_1 \frac{d\sigma}{d\mathbf{p}_1}, \quad N_2(\mathbf{p}_1, \mathbf{p}_2) = \frac{1}{\sigma_{in}} E_1 E_2 \frac{d\sigma}{d\mathbf{p}_1 d\mathbf{p}_2}, \quad (2)$$

with  $p = (E_{\mathbf{p}}, \mathbf{p})$ ,  $\Delta k = p_1 - p_2$ , and  $K = (p_1 + p_2)/2$ .

From the four assumptions made in the core-halo model<sup>12</sup>, the Bose-Einstein correlation function is found to be

$$C(\Delta k, K) \simeq 1 + \lambda_* R_c(\Delta k, K), \quad (3)$$

where the effective intercept parameter  $\lambda_*$  and the correlator of the core,  $R_c(\Delta k, K)$  are defined, respectively, as

$$\lambda_* = \lambda_*(K = p; Q_{min}) = \left[ \frac{N_c(\mathbf{p})}{N_c(\mathbf{p}) + N_h(\mathbf{p})} \right]^2 \quad (4)$$

and

$$R_c(\Delta k, K) = \frac{|\tilde{S}_c(\Delta k, K)|^2}{|\tilde{S}_c(\Delta k = 0, K = p)|^2}. \quad (5)$$

Here,  $\tilde{S}_c(\Delta k, K)$  is the Fourier transform of the core one-boson emission function,  $S_c(x, p)$ , and the subscripts  $c$  and  $h$  indicate the contributions from the core and the halo, respectively, see refs. <sup>10,12</sup> for further details. If the core-halo model is applicable, the intercept parameter  $\lambda_*$  becomes a momentum-dependent measure of the core/halo fraction as follows from eq. (4).

If the  $\eta'$  mass is decreased, a large fraction of the  $\eta'$ s will not be able to leave the hot and dense region through thermal fluctuation since they need to compensate for the missing mass by large momentum<sup>4,5,8</sup>. These  $\eta'$ s will thus be trapped in the hot and dense region until it disappears, after which their mass becomes normal again and as a consequence of this mechanism, they will have small  $p_t$ . The  $\eta'$ s then decay to pions via

$$\eta' \rightarrow \eta + \pi^+ + \pi^- \rightarrow (\pi^0 + \pi^+ + \pi^-) + \pi^+ + \pi^-. \quad (6)$$

Assuming a symmetric decay configuration ( $|p_t|_{\pi^+} \simeq |p_t|_{\pi^-} \simeq |p_t|_{\eta}$ ) and letting  $m_{\eta'} = 958$  MeV,  $m_{\eta} = 547$  MeV and  $m_{\pi^+} = 140$  MeV, the average  $p_t$  of the pions from the  $\eta'$  decay is found to be  $p_t \simeq 138$  MeV. As the  $\eta', \eta$  decays contribute to the halo due to their large decay time ( $1/\Gamma_{\eta',\eta} > 20$  fm/c), we expect a hole in the low  $p_t$  region of the effective intercept parameter,  $\lambda_* = [N_{core}(\mathbf{p})/N_{total}(\mathbf{p})]^2$ , centered around  $p_t \simeq 138$  MeV. If the masses of the  $\omega$  and  $\eta$  mesons also decrease in hot and dense matter, this  $\lambda_*(m_t)$  hole may even be deepened further, as discussed in ref.<sup>1</sup>.

## 2 Numerical simulation

In this section, we briefly review the essential steps of the numerical simulations and highlight some selected results following ref.<sup>1</sup>. In the numerical calculation of  $\lambda_*$ , we suppressed the rapidity dependence by considering the central rapidity region,  $(-0.2 < y < 0.2)$  only. As a function of  $m_t = \sqrt{p_t^2 + m^2}$ ,  $\lambda_*(m_t)$  is given by eq. (4), where the numerator represents the invariant  $m_t$  distribution of  $\pi^+$  emitted from the core and where the denominator represents the invariant  $m_t$  distribution of the total number of  $\pi^+$  emitted.

To calculate the  $\pi^+$  contribution from the halo region, the resonances  $\omega$ ,  $\eta'$ ,  $\eta$  and  $K_S^0$  were given an  $m_t$  according to the distribution<sup>10,13</sup> of

$$N(m_t) = C m_t^\alpha e^{-m_t/T_{eff}}, \quad (7)$$

where C is a normalization constant,  $\alpha = 1 - d/2$ ,  $d = 3$  is the dimension of the expansion, and the mass-dependence of the slope parameter is<sup>13,14</sup>

$$T_{eff} = T_{fo} + m\langle u_t \rangle^2. \quad (8)$$

with  $T_{fo} = 140$  MeV being the freeze-out temperature and  $\langle u_t \rangle = 0.5$  is the average transverse flow velocity. This way, the long lived resonances were generated, then they were decayed using Jetset 7.4<sup>15</sup>. The  $m_t$  distribution of the core pions was also obtained from Eqs. (7) and (8). The contributions from the decay products of the core and the halo were then added together according to their respective fractions, as given in ref.<sup>16</sup>, allowing for the

determination of  $\lambda_*(m_t)$ . The presence of the hot and dense region involves including an additional relative fraction of  $\eta'$  with a medium modified  $p_t$  spectrum. The  $p_t$  spectrum of these  $\eta'$  is obtained by assuming energy conservation and zero longitudinal motion at the boundary between the two phases,

$$m_{\eta'}^{*2} + p_{t\eta'}^{*2} = m_{\eta'}^2 + p_{t\eta'}^2, \quad (9)$$

where the  $(*)$  denotes the  $\eta'$  in the hot dense region. The  $p_t$  distribution then becomes a twofold distribution. The first part of the distribution is from the  $\eta'$  which have  $p_t^* \leq \sqrt{m_{\eta'}^2 - m_{\eta'}^{*2}}$ . These particles are given a  $p_t = 0$ . The second part of the distribution comes from the rest of the  $\eta'$ 's which have big enough  $p_t$  to leave the hot and dense region. These have the same, flow-motivated  $p_t$  distribution as the other produced resonances and were given a  $p_t$  according to the  $m_t$  distribution of eq. (8) with  $d = 3$ ; the vacuum value of the  $\eta'$  mass,  $m_{\eta'}$  was replaced by the medium-modified  $m_{\eta'}^*$  and the temperature of the hot and dense region was assumed to be  $T' = 200$  MeV.

Calculations of  $\lambda_*(m_t)$  including the hot and dense regions are shown in Fig. 1. The abundances of long-lived resonances were estimated with the help of the Fritiof model<sup>17</sup>. The two data-points shown on Fig. 1 are from S+Pb reactions at 200 AGeV as measured by the NA44 collaboration<sup>18</sup>. The lowering of the  $\eta'$  mass and the partial chiral restoration result in a deepening of the hole in the effective intercept parameter at low  $m_t$ . This “ $\lambda_*$ -hole” appears even for a modest enhancement of a factor of 3 in the  $\eta'$  production, that corresponds to a slightly reduced effective mass,  $m_{\eta'}^* = 738$  MeV. The effective masses  $m_{\eta'}^* = 403$  MeV and  $m_{\eta'}^* = 176$  MeV correspond to enhancement factors of 16 and 50, respectively. The onset of the full  $U_A(1)$  symmetry restoration in the  $m_u = m_d = m_s = 0$  limiting case corresponds to equal probability of the  $\eta'$ ,  $\eta$  and direct  $\pi$  meson production, in which case the intercept parameter  $\lambda_*$  reaches its minimum value,  $\lambda_{U_A(1)} \simeq 0.02$ , in the transverse mass region of  $m_t \leq 220$  MeV. Thus a measurement of the intercept parameter  $\lambda_*$  in a large transverse mass interval may determine whether a hole in the low  $p_t$  region exists or not. If the hole is present, its deepness characterizes the level of partial  $U_A(1)$  symmetry restoration in hot and dense matter. Full  $U_A(1)$  restoration corresponds to the maximum size of the hole, bottoming at a value of  $\lambda_{U_A(1)}$ . In this sense, the value of the  $\Delta\lambda = \lambda_*(m_t) - \lambda_{U_A(1)}$  function in the  $m_\pi \leq m_t \leq 220$  MeV region plays the role of an *experimentally measurable, effective order parameter* of  $U_A(1)$  symmetry restoration: its value is  $\Delta\lambda = 0$  for the fully symmetric phase, while the inequality  $\Delta\lambda > 0$  is satisfied if the  $U_A(1)$  symmetry is not fully restored in hot and dense hadronic matter produced in high energy heavy ion collisions.

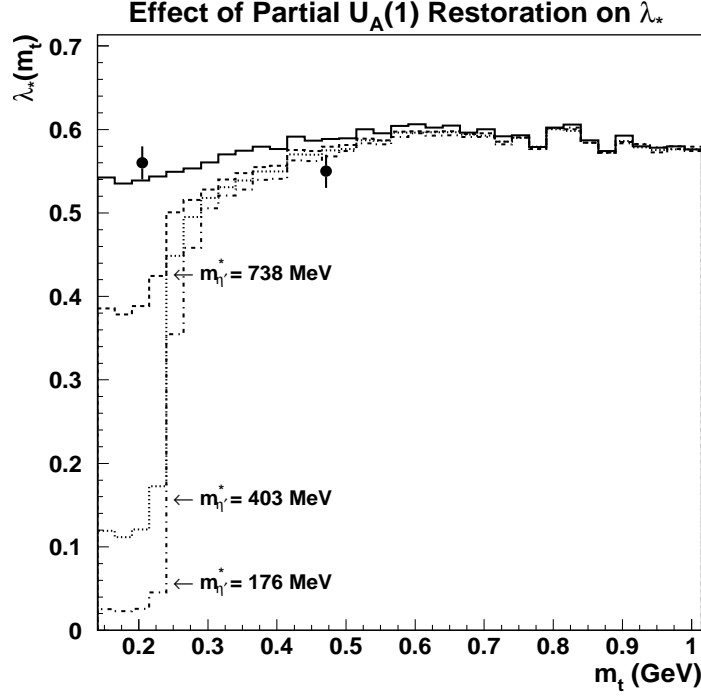


Figure 1. The solid line represents  $\lambda_*(m_t)$  assuming no partial  $U_A(1)$  symmetry restoration and normal  $\eta'$  mass, while the other lines represent the inclusion of hot and dense regions, where  $T' = 200$  MeV and partial  $U_A(1)$  symmetry restoration results in a decreased mass of the  $\eta'$  to  $m_{\eta'}^* = 738$  MeV (dashed line),  $m_{\eta'}^* = 403$  MeV (dotted line) and  $m_{\eta'}^* = 176$  MeV (dot-dashed line). All curves are calculated for  $\langle u_t \rangle = 0.5$ .

### 3 Summary

Partial  $U_A(1)$  symmetry restoration in hot and dense hadronic matter results in an observable hole for  $m_t \leq 220$  MeV region in the shape of the  $\lambda_*(m_t)$  function, that is measurable by plotting the intercept parameter of the two-pion Bose-Einstein correlation function versus the mean transverse mass of the pair. The  $\lambda_*$ -hole signal of partial  $U_A(1)$  restoration cannot be faked in a conventional thermalized hadron gas scenario, as it is not possible to create significant fraction of the  $\eta$  and  $\eta'$  mesons with  $p_t \simeq 0$  in such a case. See refs. <sup>1,19</sup> for further details and for a discussion of possible coherence effects <sup>20</sup>.

A qualitative analysis of NA44 S+Pb data suggests no visible sign of

$U_A(1)$  restoration at SPS energies. The signal of partial  $U_A(1)$  symmetry restoration should be searched for in Pb + Pb collisions at CERN SPS, and in forthcoming nuclear collisions at BNL RHIC and CERN LHC, by the experimental determination of the  $\lambda_*(m_t)$  function at  $m_t < 220$  MeV.

## Acknowledgments

We thank M. Gyulassy, U. Heinz, J. Kapusta, L. McLerran, X. N. Wang and U. Wiedemann for useful discussions. This work was supported by the OTKA Grants T024094, T026435, by the NWO - OTKA Grant N25487, by the US- Hungarian Joint Fund MAKKA 652/1998, and by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-FG02-93ER40764.

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